AD-A171 281

(12)

AD

US ARMY MATERIEL COMMAND

CONTRACT REPORT BRL-CR-554

EVALUATION OF THE DEFORMATION BEHAVIOR OF NYLON MATERIALS USED IN BALLISTIC APPLICATIONS

Battelle Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

June 1986

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER CONTRACT REPORT BRL-CR-554	2. GOVT ACCESSION NO. AD-A171 281
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) EVALUATION OF THE DEFORMATION BEHAVIOR OF NYLON MATERIALS USED IN BALLISTIC APPLICATIONS	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Mark T. Smith Edward M. Patton	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle Pacific Northwest Laboratory P.O. Box 999 Richland, WA 99352	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L162618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Ballistic Research Laboratory ATTN: SLCBR-DD-T Aberdeen Proving Ground, MD 21005-5066	12. REPORT DATE June 1986
	13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nylon	Obturator
Mechanical Properties	Compression Tests
Stress-Strain Behavior	Elastic Modulus
(	Yield Point

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The deformation behavior of two nylon 6/6 (Zytel 101) materials under various compressive loading conditions was evaluated in support of Phase III of the Projectile Foundation Moment Generation project.

(over)

20. Abstract (cont'd)

Extruded and centrifugally cast nylon, representative of current projectile obturator band materials, were tested in compression at static and dynamic loading rates. The high strain rates associated with the dynamic compression test (2600 in./in./min) resulted in significantly higher yield and compressive strengths, but only a minimal (8%) increase in elastic modulus.

Elastic constants for both materials were measured using the ultrasonic pulse-echo method, and the results show good agreement with mechanical test values. However, the experimentally determined elastic modulus values for both materials were found to be considerably higher than published book values.

The effects of an elevated confining pressure on compressive deformation behavior were evaluated using a compressive load frame equipped with a hydrostatic fluid chamber. Although test results obtained at a confining pressure of 7000 psi indicate that the extruded nylon yield behavior approaches that predicted by Von Mises' yield criterion, improvements in displacement instrumentation would be necessary before these data could be compared directly with other mechanical test results.

It is concluded that a dynamic compression test in which the specimen is exposed to a hydrostatic confining pressure would be required to fully simulate the deformation response of obturator materials under ballistic launch conditions.

TABLE OF CONTENTS

PAGE

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

Modern kinetic energy projectiles utilize nylon or nylon-based polymer materials to provide in-bore contact between the gun barrel tube and sabot components. In addition, the rear-most nylon band, known as the obturator, must provide a seal against the high propellant gas pressures used to launch the sabot/penetrator system.

Design requirements for the obturator band specify the use of DuPont Zytel 101 nylon or nylon-filled material meeting Mil-M-20693. This material, which is a nylon 6/6 composition,[1] can be produced in tubular form by centrifugal casting or pressure extrusion processes. The tubular product form is then cut and machined to specific dimensions required for the obturator design.

Although conventional material properties such as tensile and compressive strengths, flexural modulus, elongation, and density are available in the literature for Zytel 101,[1] such property values are of limited usefulness for modeling of in-bore dynamic behavior of nylon obturator bands. The inadequacy of conventional test methods to predict material behavior under ballistic loading conditions appears to be due primarily to the dependence of polymer deformation response on loading or strain rate. For semicrystalline polymers such as Zytel 101, increases in deformation rate can be expected to result in higher values of elastic modulus and yield strength due to anelastic effects. Standard ASTM procedures for tensile and compressive testing of polymeric materials specify strain rates of 0.01 to 0.10 in./in./min, while ballistic launch conditions typically impose strain rates 3 to 5 orders of magnitude higher.

The major objective of this study, conducted by Pacific Northwest Laboratory (PNL)[a] for the Ballistic Research Laboratory (BRL), was therefore to investigate and characterize the behavior of Zytel 101 nylon under test conditions that more nearly duplicate ballistic loading conditions. The experimental test plan, in addition, had the objective of determining the dependence of material properties on processing methods and specimen orientation.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

2.0 ANALYSIS OF OBTURATOR STRESS STATE

A two-dimensional, axisymmetric, finite-element model of an XM829 obturator band under ballistic loading conditions was used to determine the magnitude and state of stress for a typical value of base gas pressure. Because the obturator material is constrained between the sabot and the gun barrel tube in the radial direction, application of a gas surface pressure in the direction of the gun barrel axis produces a triaxial compressive stress state. A two-dimensional illustration of the obturator band finite-element mesh is shown in Figure 1. Calculated values for the three principal stresses, S_x, S_y, S_z, and the shear stress τ_{xy}, indicate that a triaxial compressive stress with a very low shear stress component occurs over the majority of the obturator band. Near the front of the obturator, significant shear stresses are developed such that $\tau_{xy} \cong S_x, S_y, S_z$. A complete listing of the principal stress values and shear stresses is contained in Table A1 of the Appendix.

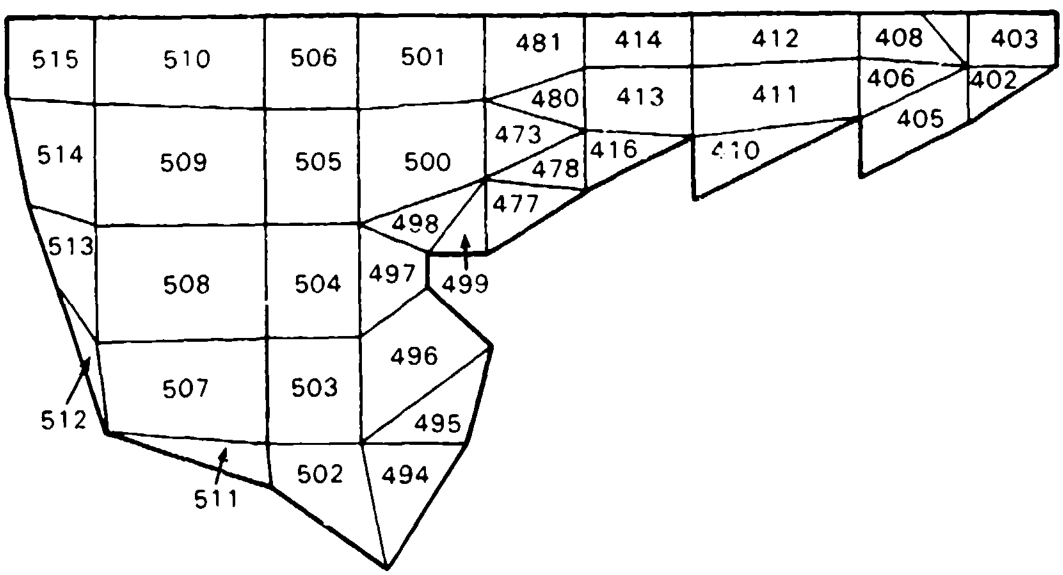

Figure 1. Two-Dimensional Obturator Finite-Element Mesh

High-strain-rate deformation of the obturator material occurs through a number of mechanisms that include the initial rise in chamber pressure, projectile travel through the gun barrel forcing cone, and cyclic deformation induced by projectile oscillations during in-bore travel. Calculation of the radial strain rate ϵ_r occurring as the obturator band traverses the forcing cone indicates a strain rate approaching 10,000 in./in./min.

3.0 EXPERIMENTAL TEST PROGRAM

The two material samples used in this study were obtained in the form of tubular sections produced by either the centrifugal casting technique or the pressure extrusion method. The centrifugally cast nylon Zytel 101, purchased from Cadillac Plastics and Chemical Company, had an outer diameter of 3.0 in. with a 0.84-in. wall thickness and was supplied in compliance with Federal Specification LP410-A. The extruded nylon Zytel 101 was produced by Polymer Corporation in the form of a 5.125-in. outer diameter tube with a 0.77-in. wall thickness, supplied as Composition A, Type 1 meeting Mil-M-20693 specifications.

The initial phase of the material characterization work involved comparative tests to determine the effects of material processing methods and material orientation on the mechanical properties of Zytel 101. Standard static compression tests were performed on both material samples utilizing specimens that had either an axial or a radial orientation. The ultrasonic pulse-echo technique was used to determine values for Young's modulus, E, shear modulus, G, and Poisson's ratio, ν, for each material type and orientation.

The second phase of the experimental test program was designed to investigate material behavior under test conditions simulating actual obturator band loading conditions. Because of the high compressive strain rates experienced by the obturator band during ballistic launch, an experimentally developed dynamic compression test was used to generate a high-strain-rate, elastic/plastic stress-strain curve for use in finite-element material modeling. In addition, a limited investigation of the stress-strain behavior of Zytel 101 under simulated hydrostatic loading conditions was performed.

3.1 EXPERIMENTAL PROCEDURE

3.1.1 Static Compression Test

Static compression tests were conducted utilizing a sub-press compression test fixture mounted in a servo-hydraulic load frame. Specimen deflection was monitored continuously with a 0.5-in. gage length axial extensometer. Load and deflection were recorded autographically using an x-y-y recorder. Machine compression rates of 0.050 in./min and 0.50 in./min were used, resulting in specimen strain rates of 0.10 in./in./min and 1.00 in./in./min, respectively. A total of three compression specimens were tested for each material type, orientation, and strain rate.

Specimen geometry selected for initial static compression testing was that of a right-hand circular cylinder having a

length of 0.750 in. and a diameter of 0.375 in. for a length-to-diameter ratio of 2.0.

Additional compression tests utilizing a 0.936-in. length by 0.375-in. diameter specimen (L/D = 2.5) were performed to determine the effect of increasing the L/D ratio on the elastic modulus and yield strength. All specimens were tested in a 30% to 40% relative humidity environment after 5 to 10 days of conditioning in the same environment.

3.1.2 Ultrasonic Determination of Elastic Constants

Previous, unreported work performed on nylon samples at PNL indicated a good correlation between values of elastic constants determined by ultrasonic techniques and those obtained from dynamic mechanical test methods. For this reason, an ultrasonic test block was machined from each of the Zytel 101 sample materials for use in determination of the elastic constants E, G, and ν. Each test block was oriented such that a flat machined surface was formed perpendicular to the axial, radial, and tangential material directions.

Ultrasonic wave velocity measurements utilizing the pulse-echo technique[2] were performed in the following manner. For each test specimen, longitudinal mode ultrasound at a frequency of 2.25 MHz and shear-mode ultrasound at 1.0 MHz were generated in the three principal material directions, and the two-way wave travel time was recorded using an oscilloscope. The appropriate wave velocities were then used in the elastic constant equations[2] to calculate values of E, G, and ν for each material type and orientation. These equations appear in the appendix of this report.

Wave velocity measurements were repeated for the extruded Zytel 101 specimen to determine experimental reproducibility.

3.1.3 Dynamic Compression Testing

A series of eight compression specimens machined from extruded Zytel 101 material were tested under dynamic loading conditions to evaluate the elastic/plastic material behavior at high strain rates. Of the eight specimens tested, four were instrumented with a single foil-type strain gage, oriented in the axial specimen direction to provide increased resolution of the elastic portion of the stress-strain curve.

All tests were conducted using a dynamic compression test fixture[3] mounted in a drop-tower test frame with a microprocessor-controlled data acquisition and analysis system. The dynamic compression fixture incorporated a high-frequency-response 50,000-lb load cell for specimen load sensing and dual-channel, linear-variable differential transducers (LVDTs) for specimen displacement measurement.

A digital oscilloscope was used to record load versus time and displacement or strain versus time signals.

Compression specimen dimensions were chosen to produce maximum loads compatible with the load cell. This resulted in a 1.563-in.-long specimen having a 0.625-in. diameter for a L/D ratio of 2.5:1.

The initial strain rate of the specimen was calculated to be 1850 in./in./min for the 3.0-in. drop height (single test) and approximately 2600 in./in./min for the 6.0-in. drop height.

3.1.4 Compression Tests on Nylon at Elevated Confining Pressures

Compression testing of two nylon Zytel 101 specimens subjected to elevated confining pressures was performed to investigate the effect of a hydrostatic constraint on material stress/strain behavior.

For each compression test a 0.625-in.-diameter, 1.563-in.-long extruded Zytel 101 specimen was placed in a compression fixture as shown in Figure 2. The specimen was then instrumented with a diametral strain gage extensometer and axial LVDTs to measure specimen displacements during loading. The instrumented compression fixture and associated loading rams before being placed in the high-pressure confining vessel are shown in Figure 3. The instrumented fixture and confining vessel were then mounted in a TerraTek Systems test frame and subjected to either a 7,000 psi or a 10,000 psi confining pressure (see

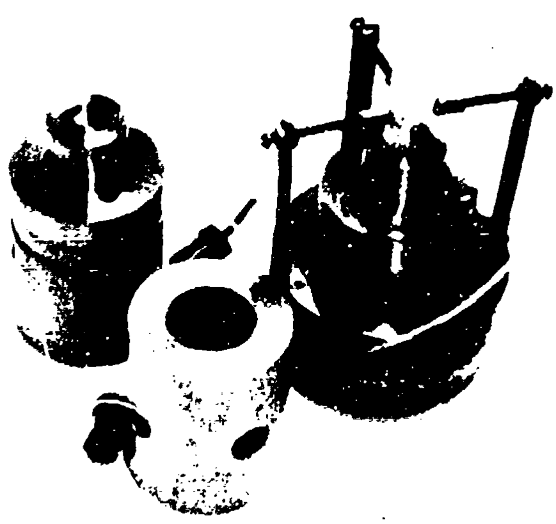

Figure 2. Hydrostatic Compression Fixture with Specimen Installed

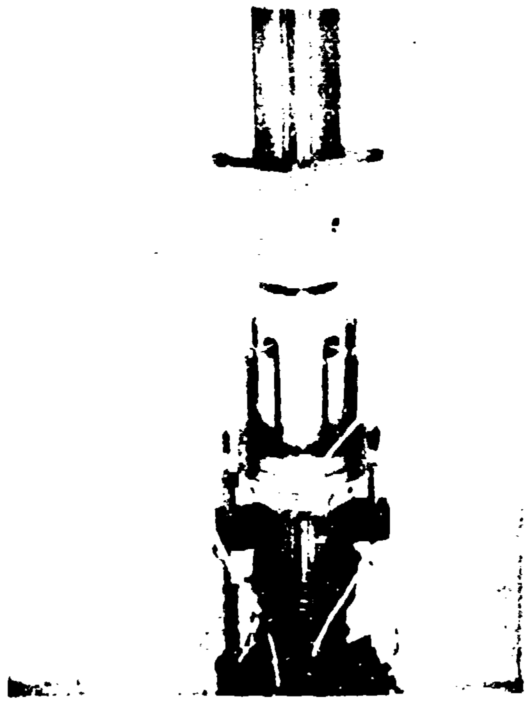

Figure 3. Instrumented Hydrostatic Compression Assembly

Figure 4.) The compression test was then initiated by displacing an axial loading ram under stroke control until a 0.2-in. displacement was reached. A computer record of load and displacement was then used to calculate and plot compressive stress as a function of specimen displacement.

Figure 4. Hydrostatic Test System

4.0 RESULTS AND DISCUSSION

4.1 STATIC COMPRESSIVE PROPERTIES

Results for static compression tests of the 2.0 L/D compression specimens are presented in Table 1. Listed are averaged values for the 0.2% offset yield strength, 1.5% offset compressive strength, and elastic modulus, E, for each material orientation and specimen strain rate. The averages of three static compression tests performed on extruded Zytel 101 specimens having an increased L/D ratio of 2.5 are also listed.

The test results presented in Table 1 for the static compression tests of extruded and centrifugally cast Zytel 101 nylon indicate that the two materials, on a comparative basis, display equivalent compressive properties. In addition, comparison of compressive properties for the axial and radial orientation of each material shows that for analytical purposes the compressive behavior can be considered isotropic. Both materials were found to display yield and compressive strengths that are in general agreement with published values; however, the modulus of elasticity of approximately 550,000 psi, which is typical of the test results, is considerably higher than published values. Although the reason for the apparently high stiffness of the test materials is not clear, two possible explanations for the high stiffness values are 1) the promotion of a higher degree of polymer crystallinity[4] through the centrifugal casting and pressure extrusion process methods, and 2) the influence of specimen geometry on deformation response.

The latter point was investigated to determine whether specimen geometry, due to end constraint effects, was promoting high apparent modulus values. The test specification (ASTM D 695) requires a specimen slenderness ratio of 11 to 15:1 for determination of elastic modulus, where the slenderness ratio (S.R.) is equal to the ratio of the specimen length to its least radius of gyration. The compression test specimens used for most of the compression tests had an S.R. equal to 8.0:1 and therefore did not meet the above requirements. However, compression tests utilizing the longer 2.5 L/D specimens were conducted to determine whether increasing the slenderness ratio had a noticeable effect on either the modulus or the yield strength. Compression test results for these specimens, which have an S.R. of 10.0, are not appreciably different from the shorter 2.0 L/D specimens. This indicates that specimen geometry, while not meeting ASTM D 695 requirements, is probably not responsible for the high elastic modulus values obtained from the compression tests.

It therefore appears more likely that processing conditions that promote increased crystallinity are responsible for the difference between published values and test results.

Table 1. Static Compression Test Results[a] for Extruded and Centrifugally Cast Nylon

Material	Operation	0.2% Offset Yield Strength, ksi	1.5% Offset Compressive Strength, ksi	Modulus Of Elasticity (E), ksi
2.0 L/D Ratio Specimen, $\dot{\varepsilon}$ = 0.10 in./in./min				
Extruded	Axial	11.1	14.0	551
	Radial	10.9	13.7	551
Centrifugally Cast	Axial	11.2	13.7	571
	Radial	10.6	12.9	516
2.0 L/D Ratio Specimen, $\dot{\varepsilon}$ = 1.00 in./in./min				
Extruded	Axial	11.7	15.0	555
	Radial	11.3	14.8	562
Centrifugally Cast	Axial	11.3	14.4	589
	Radial	11.2	13.9	543
2.5 L/D Ratio Specimen, $\dot{\varepsilon}$ = 0.10 in./in./min				
Extruded	Axial	10.9	14.2	563

(a) Test results are average of three compression tests.

The calculated values for the elastic constants E, G, and ν determined from ultrasonic velocity measurements of extruded and centrifugally cast Zytel 101 are listed in Table 2. Values reported for the extruded nylon are the average of three velocity measurements, while those reported for the centrifugally cast nylon are calculated from a single set of velocity measurements.

Table 2. Ultrasonically Determined Elastic Constants for Extruded and Centrifugally Cast Nylon

Material	Orientation	Modulus Of Elasticity (E), ksi	Shear Modulus (G), ksi	Poisson's Ratio (ν)
Extruded	Axial	559	200	0.395
	Radial	558	200	0.394
Centrifugally Cast	Axial	573	206	0.392
	Radial	573	205	0.398

The elastic constants determined by ultrasonic testing provide further support for the high stiffness values obtained from static compression testing. As presented in Table 2, the modulus of elasticity for the extruded and centrifugally cast Zytel 100 was found to be 559,000 psi and 573,000 psi, respectively, for the axial material orientation. These values are in good agreement with the modulus values determined for the static compression test and indicate that the centrifugally cast material is marginally stiffer than the extruded material. An equally important result of the ultrasonic testing is that the shear modulus, G, and Poisson's ratio, ν, calculated from the shear and longitudinal wave velocities correlate well with the respective quantities calculated independently from Hooke's Law equations for elastic constants.

This result indicates that at the high stiffness levels associated with the two test materials, deformation response approaches classical, or Hookian, behavior under ultrasonic test conditions.

4.2 DYNAMIC COMPRESSIVE PROPERTIES

The results of the dynamic compression tests are presented in Table 3 for both the noninstrumented specimens (EL-10 through EL-13) and the strain-gage instrumented specimens (EL-14 through EL-17). Due to the relatively poor signal response of the LVDT displacement measuring system utilized for specimens 10, 11, 12, and 13, no 0.2% yield strength or elastic modulus could be determined. The average values for the dynamic yield and compressive strengths and for the elastic modulus are listed at the

Table 3. Results of Dynamic Compression Tests of 2.5 L/D Ratio Extruded Nylon Specimens (Axial Material Orientation)

Specimen No.	Initial Strain Rate, in./in./min	0.2% Offset Yield Strength, ksi	1.5% Offset Compressive Strength, ksi	Modulus Of Elasticity (E), ksi
EL-10	1848	--	22.0	--
EL-11	2615	--	23.3	--
EL-12	2615	--	22.9	--
EL-13	2615	--	23.1	--
EL-14	2615	16.7	22.8	595
EL-15	2615	16.3	22.4	593
EL-16	2615	16.2	22.5	598
EL-17	2615	16.1	22.5	600
	Average	16.3	22.8	596

bottom of Table 3. Static and dynamic stress/strain curves representing average values of modulus, 0.2% yield strength, and 1.5% offset compressive strength are shown in Figure 5.

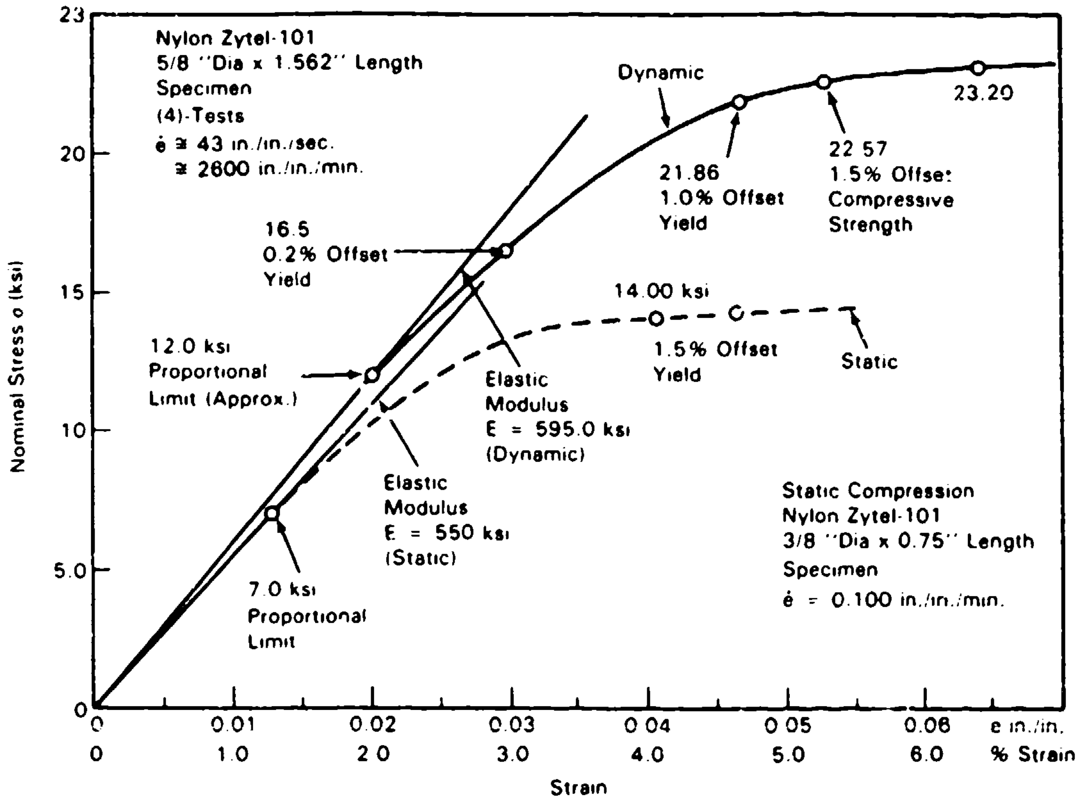

Figure 5. Static and Dynamic Stress/Strain Curves

The dynamic compression test results for the extruded Zytel 101 specimens provide information on the material compressive behavior at strain rates of the same orders of magnitude as are typical of ballistic launch conditions. Although the dynamic compression test does not fully simulate the stress state of the obturator band, it does allow material strain rate effects to be evaluated and compared with slow-strain-rate test results under similar specimen stress states.

Comparing dynamic compression test results for the four instrumented specimens with the results for the static compression tests indicates that the primary effect of increasing strain rate is to increase the materials yield and compressive strength levels.

Using average values for the 0.2% yield and 1.5% compressive strengths for comparison indicates that increasing the specimen strain rate from 0.100 in./in./min to approximately 2600 in./in./min results in a 47% and 63% increase in yield and 1.5% compressive strength, respectively. In contrast to the relatively large increases in strength levels, comparison of

average modulus of elasticity for the two strain rates shows only an 8% increase at the higher testing rates.

The unpublished results for static and dynamic tensile tests of Zytel 101 nylon performed at PNL indicate a much stronger strain rate dependence for material properties in the tensile deformation mode. In this work, static tensile testing performed at a strain rate of 0.04 in./in./min resulted in an elastic modulus value of 370,000 psi, while the dynamic tensile test ($\dot{\varepsilon}$ = 2,545 in./in./min) indicated an E value of 526,000 psi. Comparison of the static and dynamic 0.2% yield strength indicated that increasing strain rate resulted in an increase in yield strength of approximately 58%.

These results are particularly interesting because they indicate that for small, primarily elastic strains, the dominant compressive deformation mechanism is relatively insensitive to strain rate effects while comparable changes in strain rate result in significant anelastic behavior for Zytel 101 in tension. However, increases in strain rates appear to produce essentially equal increases in measured strength levels for Zytel 101 in both the tensile and the compressive deformation mode.

4.3 HYDROSTATIC COMPRESSIVE PROPERTIES

As previously mentioned, a limited effort was made to evaluate the compression properties of Zytel 101 under an elevated confining pressure. The two tests conducted on the 0.625-in.-diameter extruded compression specimens were performed by superimposing an axial displacement on a specimen subjected to an elevated confining pressure of either 7,000 or 10,000 psi. Because of instrumentation problems, only the results of the first test, conducted at 7,000 psi confining pressure, are reported here. A plot of stress for this test as a function of LVDT displacement is shown in Figure 6. Graphical estimates of the modulus of elasticity, E, and 0.2% offset yield strength were made and indicate a modulus of approximately 530,000 psi, 13.0 ksi yield strength, and a 1.5% compressive strength of 15.5 ksi. Material strain rate for the test was 0.032 in./in./min.

Although the results are in general agreement with the more conventional compression test results reported previously, experimental difficulties with the LVDT displacement measuring system make specific comparisons difficult.

The significant result of this test is that subjecting the nylon specimen to an elevated confining pressure, which simulates hydrostatic loading conditions, apparently does not have a major effect on the axial yield strength or modulus of elasticity. This would indicate that, in contrast to conventional polymer theory,[4] the yield behavior of extruded Zytel 101 approaches that predicted by the Von Mises' criterion.

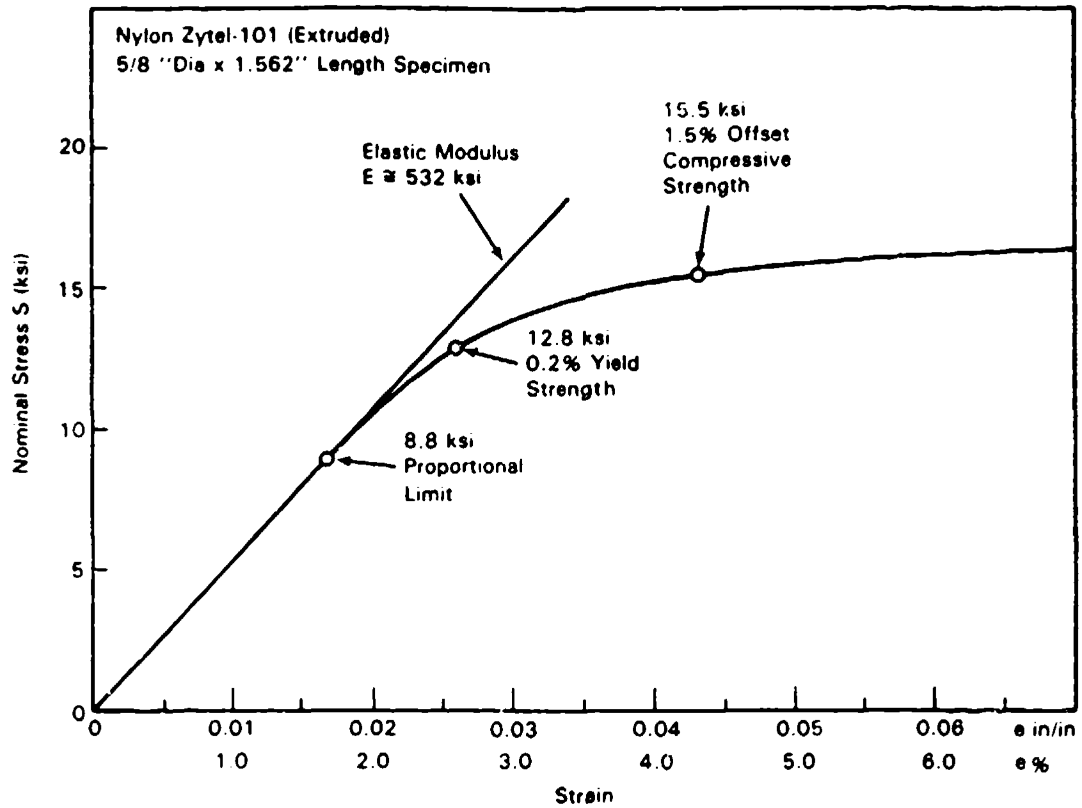

Figure 6. Hydrostatic Compressive Stress/Strain Curve

5.0 CONCLUSIONS AND RECOMMENDATIONS

1) The static and dynamic compression tests subject the nylon test material to a stress state that is more representative of obturator band loading conditions than is possible with uniaxial tensile tests.

2) Comparison of compression test results for the two material processing methods and orientation indicates that both the extruded and the centrifugally cast Zytel 101 materials can be considered equivalent and isotropic in compressive properties.

3) The modulus of elasticity in compression for Zytel 101, determined by three different test methods, was found to be relatively insensitive to strain rate effects. In contrast, increases in strain rate were found to increase the yield and 1.5% compressive strength by an average of 47% and 63%, respectively.

4) Limited experimental results obtained for deformation of nylon at elevated confining pressures indicate that the hydrostatic stress component has a relatively small influence on the elastic modulus and yield strength. Further testing with improved displacement instrumentation would be required to confirm this observation.

5) To fully simulate the loading conditions associated with nylon obturator bands during ballistic launch conditions would require development of a dynamic compression test in which an elevated confining pressure could be superimposed.

REFERENCES

1. Modern Plastics Encyclopedia, 1981-82, Vol. 58, No. 10A, McGraw-Hill, New York.

2. Krautkramer, J., and Krautkramer, H., 1977, Ultrasonic Testing of Materials, 2nd Ed., Springer-Verlag, New York.

3. Alder, W.F., James, T.W., and Kukuchek, P.E., 1981, Development of a Dynamic Compression Fixture for Brittle Materials, Technical Report CR-81-918, Effects Technology, Inc., Santa Barbara, California.

4. Dieter, G.E., 1976, Mechanical Metallurgy, 2nd Ed., McGraw-Hill, New York.

APPENDIX

CALCULATION OF MATERIAL ELASTIC CONSTANTS FROM MEASURED ULTRASONIC WAVE VELOCITIES

$$\text{Acoustic Velocity Ratio } r = \frac{C_l}{C_S} \quad (1)$$

$$\text{Shear Modulus } G = \rho C_S^2 \quad (2)$$

$$\text{Poisson's Ratio } \nu = \frac{1 - r^2/2}{1 - r^2} \quad (3)$$

$$\text{Young's Modulus } E = G\left[\frac{4 - 3r^2}{1 - r^2}\right] \quad (4)$$

where C_l = longitudinal wave velocity

C_S = shear wave velocity

ρ = mass density of Zytel 101.

Table A1. Finite Element Obturator Stress Listing

Element Number (STIF 42)	S_x psi	S_y psi	T_{xy} psi	S_z psi
402	-10899	-14474	-2793	-11150
403	-2479	-5320	-3120	-3154
405	1975	1528	-1388	1887
406	-9257	-12774	-6704	-9671
407	-5624	-9245	-279	-6298
408	-3271	-12035	-3325	-6594
410	-5069	-6028	-1100	-4808
411	-18552	-25528	-10732	-19945
412	-20994	-28803	-2994	-21932
413	-38302	-48929	-9084	-38543
414	-35378	-41499	-2296	-34237
416				
477	-25624	-51123	-10655	-34127
478	-45043	-66657	-10671	-49592
479	-49427	-57920	-4898	-47495
480	-44878	-54097	-5192	-43883
481	-52514	-54562	-2080	-47608
494	-39046	-62902	422.3	-44920
495	-56213	-76961	2886	-58995
496	-58227	-92119	-7867	-66528
497	-81202	-72622	7407	-68469
498	-48991	-75580	-6543	-54933
499	-87191	-1.27 E6	-9023	-95468
500	-56927	-65967	-2970	-54033
501	-58299	-58932	-1579	-52072
502	-65452	-84326	6732	-64983
503	-55996	-67085	654.8	-52333
504	-58784	-62792	2046	-52599
505	-57473	-61346	518	-51985
506	-60308	-60203	-816	-53444
507	-65606	-66572	-352	-54912
508	-63346	-64073	432	-54237
509	61996	62080	1841	-53665
510	-63618	-58330	1609	-53661
511	-66354	-68811	-1464	-55903
512	-67308	-66630	431	-56210
513	75900	-73375	217	-64010
514	-71863	-69816	2240	-61515
515	-71004	-63640	2078	-59844

DISTRIBUTION LIST

No. of Copies	Organization
12	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22314
1	Director of Defense Research & Engineering (OSD) ATTN: R. Thorkildsen Washington, DC 20301
1	Director of Defense Research & Engineering (OSD) ATN: J. Persh Washington, DC 20301
1	Director Defense Advanced Research Projects Agency 1400 Wilson Boulevard Arlington, VA 22209
1	Director Institute of Defense Analysis ATTN: Documents Acquisition 1801 Beauregard Street Alexandria, VA 22311
1	HQDA (DAMA-MS) Washington, DC 20310
1	HQDA (DAMA-ZA) Washington, DC 20310
1	HQDA (DAMA-ZD), H. Woodall Washington, DC 20310
1	HODA (DAMA-ARZ-A), M.E. Lasser Washington, DC 20310
2	HQDA (DAMA-CSM-VA) (DAMA-CSM-CA) Washington, DC 20310

No. of Copies	Organization
1	HQDA (DAMA-CSS-5), J. Bryant Washington, DC 20310
1	HQDA DAMA-ART-M Washington, D.C. 20310
10	Central Intelligence Agency Office of Central Reference Dissemination Branch Room GE-47 HQS Washington, DC 20502
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Materiel Command ATTN: DRCLDC 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Materiel Command ATTN: DRCDE Deputy Director 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Materiel Command ATTN: DRCDE-R 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Materiel Command 5001 Eisenhower Avenue Alexandria, VA 22333

DISTRIBUTION LIST

No. of Copies	Organization
8	Commander US Army AMCCOM ATTN: SMCAR-LCA, A. Moss SMCAR-LC, SMCAR-SE SMCAR-SA SMCAR-AC SMCAR-LCU-SE, J. Pearson SMCAR-LCA-M, F. Saxe SMCAR-LCU-SS, R. Botticelli Dover, NJ 07801
5	Commander US Army AMCCOM, ARDC ATTN: SMCAR-SCS SMCAR-SCS-E SMCAR-SCF SMCAR-SCS SMCAR-SCF Dover, NJ 07801
2	Commander US Army AMCCOM, ARDC ATTN: SMCAR-TSS Dover, NJ 07801
4	Commander US Army AMCCOM, ARDC ATTN: SMCAR-TD SMCAR-TDA SMCAR-TDS SMCAR-TDC, C. Larson Dover, NJ 07801
7	Commander US Army AMCCOM, ARDC ATTN: SMCAR-LCA, B. Knutelski SMCAR-LCR-R, E.H. Moore III SMCAR-LCS, J. Gregorits SMCAR-LCS-D, K. Rubin SMCAR-LCA, T. Davidson SMCAR-LCA, E. Friedman SMCAR-LCA, A. Lehberger Dover, NJ 07801
5	Commander US Army AMCCOM, ARDC ATTN: SMCAR-LCU, E. Barrieres SMCAR-LCU, R. Davitt SMCAR-LCU-M, D. Robertson SMCAR-LCU-M, M. Weinstock SMCAR-LCA-M, C. Larson Dover, NJ 07801
7	Commander US Army AMCCOM, ARDC ATTN: SMCAR-SCA, C.J. McGee SMCAR-SCA, S. Goldstein SMCAR-SCA, F.P. Puzychki SMCAR-SCA, E. Jeeter SMCAR-SCF, M.J. Schmitz SMCAR-SCF, L. Berman SMCAR-SCZ, P. Petrella Dover, NJ 07801
9	Commander US Army AMCCOM, ARDC ATTN: SMCAR-SCM SMCAR-SCM, E. Bloore SMCAR-SCM, J. Mulnerin SMCAR-SCS, B. Brodman SMCAR-SCS, T. Hung SMCAR-SCA, W. Gadomski SMCAR-SCA, E. Malatesta SMCAR-SCA-T, P. Benzkofer SMCAR-SCA-T, F. Dahdouh Dover, NJ 07801
3	Commander US Army AMCCOM, ARDC ATTN: SMCAR-LCA, W. Williver SMCAR-LCA, S. Bernstein SMCAR-LCA, G. Demitrack Dover, NJ 07801

DISTRIBUTION LIST

No. of Copies	Organization
4	Commander US Army AMCCOM, ARDC ATTN: SMCAR-LCA, S. Yim SMCAR-LCA, L. Rosendorf SMCAR-LCA, S.H. Chu SMCAR-LCW, R. Wrenn Dover, NJ 07801
6	Director Benet Weapons Laboratory Armament R&D Center US Army AMCCOM, ARDC ATTN: SMCAR-LCB-TL SMCAR-LCB SMCAR-LCB-RA, R. Scanlon SMCAR-LCB-RM, M. Scarullo SMCAR-LCB-RA, R. Soanes, Jr. SMCAR-LCB-RA, J. Vasilakis Watervliet, NY 12189
7	Director US Army AMCCOM, ARDC Benet Weapons Laboratory ATTN: SMCAR-LCB-RA, T. Simkins SMCAR-LCB-D, J. Zweig SMCAR-LCB-RA. G. Pflegl SMCAR-LCB-M, J. Purtell SMCAR-LCB-RA, R. Racicot SMCAR-LCB-DS, J. Santini SMCAR-LCB-RA, J. Wu Watervliet, NY 12189
2	Commander US Army AMCCOM, ARDC ATTN: SMCAR-SC SMCAR-SC, B. Shulman Dover, NJ 07801
2	Commander US Army AMCCOM, ARDC ATTN: Army Fuze Mgt Project Office SMCAR-FU Dover, NJ 07801
2	Commander US Army AMCCOM, ARDC ATTN: SMCAR-DP Development Project Office for Selected Ammunitions Dover, NJ 07801
2	Commander US Army AMCCOM, ARDC ATTN: Product Assurance Directorate SMCAR-QA Dover, NJ 07801
1	Commander US Army AMCCOM, ARDC ATTN: SMCAR-NS Dover, NJ 07801
1	Commander US Army AMCCOM, ARDC ATTN: L. Goldsmith Dover, NJ 07801
1	Commander US Army ARRCOM ATTN: SMCAR-TSE-SW, R. Radkiewicz Rock Island, IL 61299
2	Commander US Army ARRCOM ATTN: SMCAR-LEP-L SMCAR-TSE-SW, G. Strahl Rock Island, IL 61299

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander US Army ARRCOM ATTN: SARRI-RLS Rock Island, IL 61299
1	Commander US Army Aviation Research and Development Command ATTN: AMSAV-E 4300 Goodfellow Blvd. St. Louis, MO 63120
2	Director US Army Air Mobility Research and Development Laboratory ATTN: Hans Mark R.L. Cohen Ames Research Center Moffett Field, CA 94035
2	Director US Army Research & Technology Laboratories Ames Research Center Moffett Field, CA 94035
2	Director US Army Research & Technology Laboratories ATTN: DAVDL-AS, DAVDL-AS, Ames Research Center Moffett Field, CA 94035
1	Commander ERADCOM Technical Library ATTN: DELSD-L (Reports Section) Fort Monmouth, NJ 07703-5301
1	Commander Atmospheric Sciences Lab. USA Electronics Research and Development Command ATTN: DELAS-EO-MO, R.B. Gomez White Sands Missile Range NM 88002
3	Commander USA Harry Diamond Lab. ATTN: DELHD-I-TR, H.D. Curchak DELHD-I-TR, H. Davis DELHD-S-QE-ES, 2800 Powder Mill Road Adelphi, MD 20783
1	Commander USA Harry Diamond Labs. ATTN: DELHD-TA-L 2800 Powder Mill Road Adelphi, MD 20783
1	Director Night Vision Laboratory Fort Belvoir, VA 22060
2	Commander US Army Missile Command Research, Development and Engineering Center ATTN: AMSMI-RD AMSMI-YDL Redstone Arsenal, AL 35898-5500
1	Director US Army Missile and Space Intelligence Center ATTN: AIAMS-YDL Redstone Arsenal, AL 35898-5500

DISTRIBUTION LIST

No. of Copies	Organization
2	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905
2	Commander US Army Missile Command ATTN: DRCPM-TO DRCPM-HD Redstone Arsenal, AL 35898
1	Commander US Army Mobility Equipment Research & Development Cmd Fort Belvoir, VA 22060
3	Commander US Army Tank Automotive Cmd ATTN: AMSTA-TSL AMSTA-ZSA, R. Beck AMSTA-NS Warren, MI 48397-5000
1	Commander US Army Natick Research and Development Command ATTN: DRDNA-DT Natick, MA C.762
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SL White Sands Missile Range, NM 88002
2	President US Army Armor and Engineering Board ATTN: ATZK-AE-CV ATZK-AE-IN, L. Smith Fort Knox, KY 40121
3	Commander US Army Research Office ATTN: R. Weigle E. Saibel J. Chandra P.O. Box 12211 Research Triangle Park NC 27709-2211

No. of Copies	Organization
3	Commander US Army Research Office P.O. Box 12211 ATTN: Technical Director Engineering Division Metallurgy & Materials Division Research Triangle Park, NC 27709-2211
4	Director US Army Mechanics and Materials Research Center ATTN: Director (3 cys) DRXMR-ATL (1 cy) Watertown, MA 02172
2	Commander US Army Materials and Mechanics Research Center ATTN: J. Mescall Tech. Library Watertown, MA 02172
1	Commander US Army Training and Doctrine Command ATTN: TRADOC Lib, Fort Monroe, VA 23651
1	Commander US Army Armor School ATTN: Armor Agency, MG Brown Fort Knox, KY 40121
1	Commander US Army Field Artillery School ATTN: Field Artillery Agency Fort Sill, OK 73503
1	Superintendent Naval Postgraduate School ATTN: Dir of Lib Monterey, CA 93940
1	Commander USACAC & Fort Leavenworth Ft. Leavenworth, KS 66027-5080

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander US Army Combat Development Experimentation Command ATTN: Tech Info Center Bldg. 2925, Box 22 Fort Ord, CA 93941
1	Commander Naval Sea Systems Command ATTN: 9132 Washington, DC 20362
1	Commander Naval Sea Systems Command (SEA-62R41) ATTN: L. Pasiuk Washington, DC 20362
1	Commander Naval Research Laboratory ATTN: H. Peritt, Code R31 Washington, DC 20375
1	Commander Naval Ship Research and Development Center Bethesda, MD 20084
5	Commander Naval Research Laboratory ATTN: W.J. Ferguson C. Sanday H. Pusey Tech Library Washington, DC 20375
6	Commander Naval Surface Weapons Center ATTN: Code X211, Lib E. Zimet, R13 R.R. Bernecker, R13 J.W. Forbes, R13 S.J. Jacobs, R10 K. Kim, R13 Silver Springs, MD 20910
3	Commander Naval Surface Weapons Center ATTN: Code E-31, R.C. Reed M.T. Walchak Code V-14, W.M. Hinckley Silver Spring, MD 20910
5	Commander Naval Surface Weapons Center ATTN: Code G-33, T.N. Tschirn Code N-43, J.J. Yagla L. Anderson G. Soo Hoo Code TX, W.G. Soper Dahlgren, VA 22448
1	Commander Naval Weapons Center China Lake, CA 93555
1	Commander Naval Weapons Center ATTN: J. O'Malley China Lake, CA 93555
2	Commander Naval Weapons Center ATTN: Code 3835, R. Sewell Code 3431, Tech Lib China Lake, CA 93555
2	Commander US Naval Weapons Center ATTN: Code 608, R. Derr Code 4505, C. Thelen China Lake, CA 93555
3	Commander Naval Weapons Center ATTN: Code 4057 Code 3835, B. Lundstrom Code 3835, M. Backman China Lake, CA 93555
1	Commander Naval Ordnance Station Indian Head, MD 20640

DISTRIBUTION LIST

No. of Copies	Organization
2	Commander Naval Ordnance Station ATTN: Code 5034, Ch. Irish T.C. Smith Indian Head, MD 20640
1	Office of Naval Research ATTN: Code ONR 439, N. Perrone Department of the Navy 800 North Quincy Street Arlington, VA 22217
1	Commandant US Marine Corps ATTN: AX Washington, DC 20380
1	AFATL/DLXP ATTN: W. Dittrich Eglin AFB, FL 32542
1	AFATL/DLD ATTN: D. Davis Eglin AFB, FL 32542
2	ADTC/DLJW Eglin AFB, FL 32542
1	ADTC/DLODL, Tech Lib Eglin AFB, FL 32542
1	AFWL/SUL ATTN: J.L. Bratton Kirtland AFB, NM 87117
1	AFML/LLN (T. Nicholas) Wright-Patterson AFB, OH 45433
2	ASD (XROT, G. Bennett; ENSSS, Martin Lentz) Wright-Patterson AFB, OH 45433

No. of Copies	Organization
2	Battelle Memorial Institute ATTN: L.E. Hulbert J.E. Backofen, Jr. 505 King Avenue Columbus, OH 43201
3	Battelle Pacific Northwest Laboratory ATTN: M.T. Smith F.A. Simonen L.A. Strope P.O. Box 999 Richland, WA 99352
1	Bell Telephone Labs. Inc. Mountain Avenue Murray Hill, NJ 07971
1	Director Lawrence Livermore Laboratory P.O. Box 808 Livermore, CA 94550
2	Director Lawrence Livermore Laboratory ATTN: E. Farley, L9 D. Burton, L200 Livermore, CA 94550
3	Director Lawrence Livermore Laboratory ATTN: T.T. Chaio, L338 M.L. Wilkins R.M. Christensen, L338 Livermore, CA 94550
1	Director NASA - Ames Research Center Moffett Field, CA 94035
2	Forrestal Research Center Aeronautical Engineering Lab. ATTN: S. Lam A. Eringen Princeton, NJ 08540
1	Sandia National Laboratories ATTN: D.E. Waye Livermore, CA 94550

DISTRIBUTION LIST

No. of Copies	Organization
1	AFELM, The Rand Corporation ATTN: Library-D 1700 Main Street Santa Monica, CA 90406
1	Aircraft Armaments Inc. ATTN: John Hebert York Road & Industry Lane Cockeysville, MD 21030
2	ARES, Inc. ATTN: Duane Summers Phil Conners Port Clinton, OH 43452
2	AVCO Coroporation Structures and Mechanics Dept ATTN: W. Broding J. Gilmore 201 Lowell Street Wilmington, MA 01887
3	BLM Applied Mechanics Consultants ATTN: A. Boresi R. Miller H. Langhaar 3310 Willett Drive Laramie, WY 82070
1	Martin Marietta Laboratories ATTN: J.I. Bacile Orlando, FL 32805
1	H.P. White Laboratory 3114 Scarboro Road Street, MD 21154
1	CALSPAN Corporation ATTN: E. Fisher P.O. Box 400 Buffalo, NY 14225
1	FMC Corporation Ordnance Engineering Division San Jose, CA 95114
1	Kaman-Tempo ATTN: E. Bryant 715 Shamrock Road Bel Air, MD 21014
1	General Electric Armament and Electrical Systems ATTN: D.A. Graham Lakeside Avenue Burlington, VT 05402
1	Olin Corporation Badger Army Ammunition Plant ATTN: R.J. Thiede Baraboo, WI 53913
1	S&D Dynamics, Inc. ATTN: M. Soifer 755 New York Avenue Huntington, NY 11743
1	Southwest Research Institute ATTN: P.A. Cox 8500 Culebra Road San Antonio, TX 78228
1	Southwest Research Institute ATTN: T. Jeter 8500 Culebra Road San Antonio, TX 78228
1	University of Dayton Research Institute ATTN: S.J. Bless Dayton, OH 45469
1	University of Delaware Department of Mechanical Engineering ATTN: H. Kingsbury Newark, DE 19711
6	University of Illinois College of Engineering ATTN: A. Zak (2) D. C. Drucker Urbana, IL 61801

DISTRIBUTION LIST

No. of Copies	Organization
2	University of Iowa College of Engineering ATTN: R. Benedict E.J. Haug Iowa City, IA 52240
1	Rutgers University Dept. of Mechanical and Aerospace Engineering P.O. Box 909 ATTN: T.W. Lee Piscataway, NJ 08854
1	University of Wisconsin Mechanical Engineering Depart ATTN: S.M. Wu Madison, WI 53706
1	University of Wisconsin Mathematics Research Center 610 Walnut Street ATTN: B. Noble Madison, WI 53706
1	AFFDL/FB (J. Halpin) Wright-Patterson AFB, OH 45433
3	Honeywell, Inc. Defense Systems Division 5901 South City Road Edina, MN 55436
4	Los Alamos Scientific Lab. ATTN: Tech Lib J. Taylor R. Karpp U.F. Kocks P.O. Box 808 Livermore, CA 94550
4	Sandia National Laboratories ATTN: L. Davison P. Chen L. Bertholf W. Herrmann Albuquerque, NM 87115
4	SRI International ATTN: D. Curran L. Seaman Y. Gupta G.R. Abrahamson 333 Ravenswood Avenue Menlo Park, CA 94025
5	Brown University Division of Engineering ATTN: R. Clifton H. Kolsky A. Pipkin P. Symonds J. Martin Providence, RI 02912
3	California Institute of Technology Division of Engineering and Applied Science ATTN: J. Miklowitz E. Sternberg J. Knowles Pasadena, CA 91102
1	University of California at Los Angeles Department of Mechanics ATTN: W. Goldsmith 504 Hilgard Avenue Los Angeles, CA 90024
1	Drexel Institute of Technology Wave Propagation Research Center ATTN: P.C. Chou 32nd and Chestnut Streets Philadelphia, PA 19104
1	Harvard University Division of Engineering and Applied Physics ATTN: G. Carrier Cambridge, MA 02138

DISTRIBUTION LIST

No. of Copies	Organization
1	Iowa State University Department of Engineering Science and Mechanics ATTN: C.P. Burger Ames, IA 50010
2	Iowa State University Engineering Research Lab. ATTN: G. Nariboli A. Sedov Ames, IA 50010
4	The Johns Hopkins University ATTN: J. Bell R. Green R. Pond, Sr. C. Truesdell 34th and Charles Streets Baltimore, MD 21218
1	Louisiana State University Department of Mechanical Engineering ATTN: W. Sharpe P.O. Box 16006 Baton Rouge, LA 70803
4	Massachusetts Institute of Technology ATTN: R. Probstein A.S. Argon F. McClintock K.J. Bathe 77 Massachusetts Avenue Cambridge, MA 02139
1	New Mexico Institute of Mining and Technology Terra Group Socorro, NM 87801
1	Rensselaer Polytechnic Inst. Department of Mechanical Engineering ATTN: E. Krempl Troy, NY 12181
2	Southwest Research Institute Department of Mechanical Sciences ATTN: U. Lindholm W. Baker 8500 Culebra Road San Antonio, TX 78228
2	University of Delaware Department of Mechanical Engineering ATTN: J. Vinson M. Taya Newark, DE 19711
3	University of Florida Department of Engineering Science and Mechanics ATTN: C. Sciammarilla L. Malvern E. Walsh Gainesville, FL 32611
2	University of Illinois at Chicago Circle College of Engineering Dept. of Materials Engineering ATTN: A. Schultz T.C.T. Ting P.O. Box 4348 Chicago, IL 60680
2	University of Minnesota Department of Engineering Mechanics ATTN: R. Fosdick J. Erickson Minneapolis, MN 55455
1	Commander Armament R&D Center U.S. Army AMCCOM ATTN: SMCAR-TSS Dover, NJ 07801

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander Armament R&D Center U.S. Army AMCCOM ATTN: SMCAR-TDC Dover, NJ 07801
1	Commander U.S. Army Armament, Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299
1	Ccommander U.S. Army Aviation Research and Develpment Command ATTN: AMSAV-E 4300 Goodfellow Blvd St. Louis, MO 63120
1	Commander U.S. Army Communications - Electronics Command ATTN: AMSEL-ED Fort Monmouth, NJ 07703
1	Commander U.S. Army Development and Employment Agency ATTN: MODE-TED-SAB Fort Lewis, WA 98433
1	Air Force Armament Laboratory ATTN: AFATL/DLODL Eglin AFB, FL 32542-5000
6	Sandia National Laboratories ATTN: C.W. Robinson G.A. Benedetti M.L. Callabresi D.J. Bammann M.R. Birnbaum N.A. Lapetina Livermore, CA 94550
1	Yale University Department of Engineering and Applied Science ATTN: A. Phillips New Haven, CT 06520
2	Washington State University Department of Physics ATTN: G.E. Duvall R. Fowles Pullman, WA 99163
	Aberdeen Proving Ground
	Dir, USAMSAA ATTN:AMXSY-D AMXSY-MP, H. Cohen AMXSY-G, E. Christman AMXSY-OSD, H. Burke AMXSY-G, R.C. Conroy AMXSY-LM, J.C.C. Fine Dir, USAHEL ATTN:A.H. Eckles, III Cdr, USATECOM ATTN:AMSTE-CE AMSTE-TO-F Dir, USCRDC, Bldg. E3516, EA ATTN:SMCAR-RSP-A SMCAR-MU SMCAR-SPS-IL SMCAR-CLD SMCAR-MS SMCAR-CLN SMCAR-CLN-D, L. Shaff SMCAR-CLN-D, F. Dagostin SMCAR-CLN-D, C. Hughes SMCAR-CLN, J. McKivrigan SMCAR-CLJ-L

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number________________ Date of Report________

2. Date Report Received________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.)________

4. How specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.)________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided or efficiencies achieved, etc? If so, please elaborate.________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.)

CURRENT ADDRESS

Name

Organization

Address

City, State, Zip

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

Name

Organization

Address

City, State, Zip

(Remove this sheet along the perforation, fold as indicated, staple or tape closed, and mail.)

END
10-86
DTIC